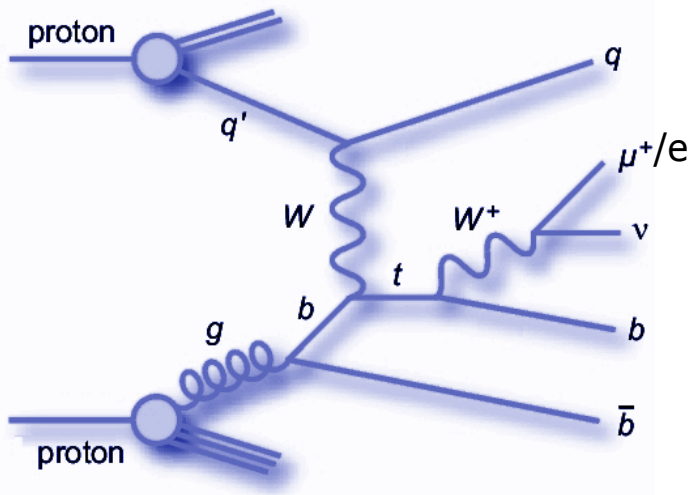# Measurement of the Single Top Quark t-Channel Cross section in pp Collisions at sqrt(s) = 7 TeV with the CMS Experiment

CMS PAS TOP-10-008

- Introduction and Event Selection

- 2D Analysis

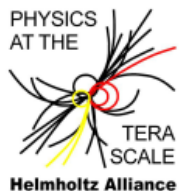- Boosted Decision Tree (BDT) Analysis

- Combination and Results

Dennis Klingebiel
klingebiel@physik.rwth-aachen.de
RWTH Aachen, Physics Institute IIIA

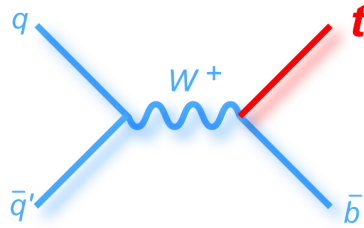**on Behalf of the CMS Collaboration**

GEFÖRDERT VOM
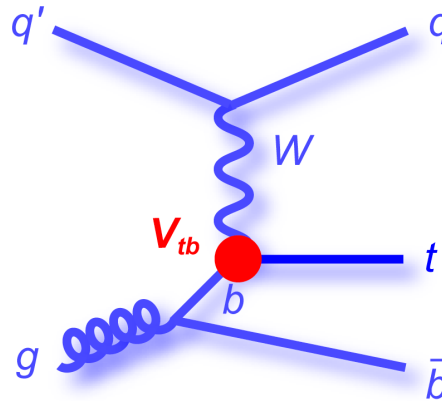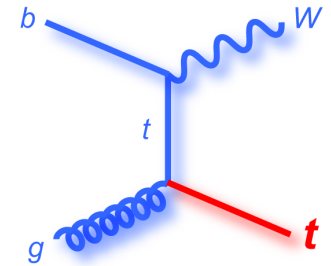
Bundesministerium für Bildung und Forschung

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

DIS 2011, Newport News, 14th April 2011

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Introduction

s-channel

t-channel

associated production (tW)

Cross sections @ NLO

|	s-channel	t-channel	tW
LHC 7 TeV:	4.6 pb	**64.3 pb**	10.6 pb
Tevatron 1.96 TeV:	0.9 pb	2 pb	0.09 pb

- 2010 Dataset (36pb^{-1}):
    - First measurement of t-channel single top quark production
      → Other channels are treated as background
    - Direct measurement of V_{tb}
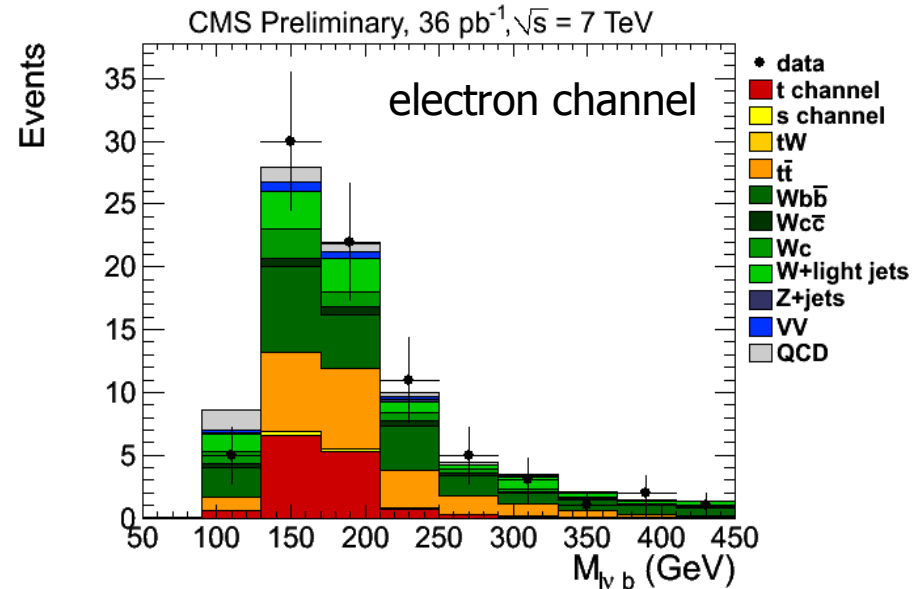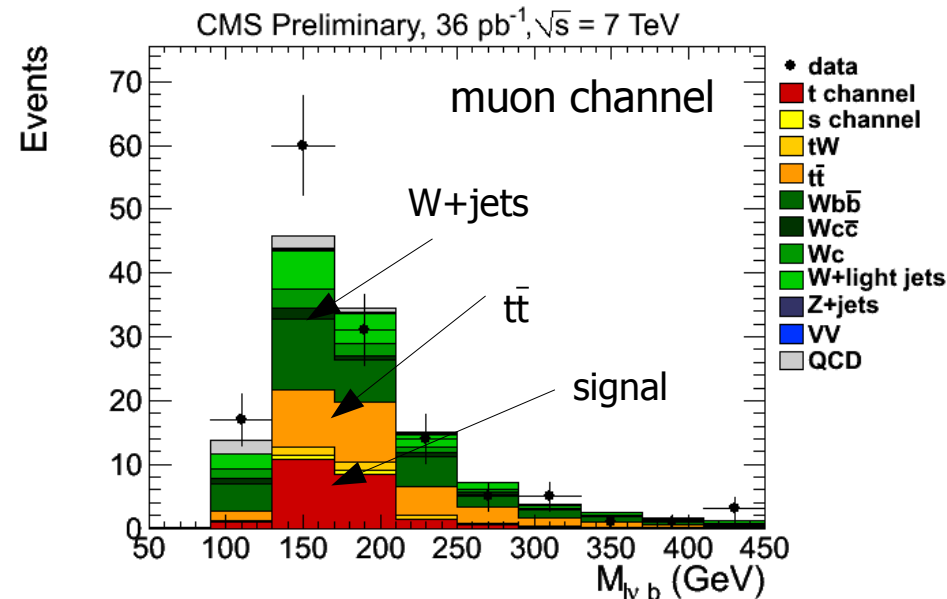   → Probe EW interactions of the top quark in a new energy regime

Event Selection

- **Trigger: Single μ/e**

- **Existence of a good primary vertex**

- **Exactly one muon (electron) with**

  - $p_T > 20$ GeV $(E_T > 30$ GeV), $|\eta| < 2.1$ (2.5)

  - relative isolation < 0.1 $relIso = \frac{chargedHadronIso + neutralHadronIso + photonHadronIso}{p_T}$

  - 2D impact parameter to primary vertex < 0.004cm (0.02 cm)

  - Dilepton veto, Z veto (el. channel only)

- **Exactly two anti-kt 5 Particle Flow jets with**

  - $E_T > 30$ GeV, $|\eta| < 5$

  - one (tight) b-tagged jet (track counting algorithm)

  - $\Delta\phi$ (jet1, jet2) < 3 (BDT analysis)

  - Loose b-veto on 2nd jet (track counting algorithm) (2D analysis)

- **Transverse W boson mass > 40 GeV (50 GeV)**

3

W^+ → l^+ ν

t → b

$\not{E}_T$
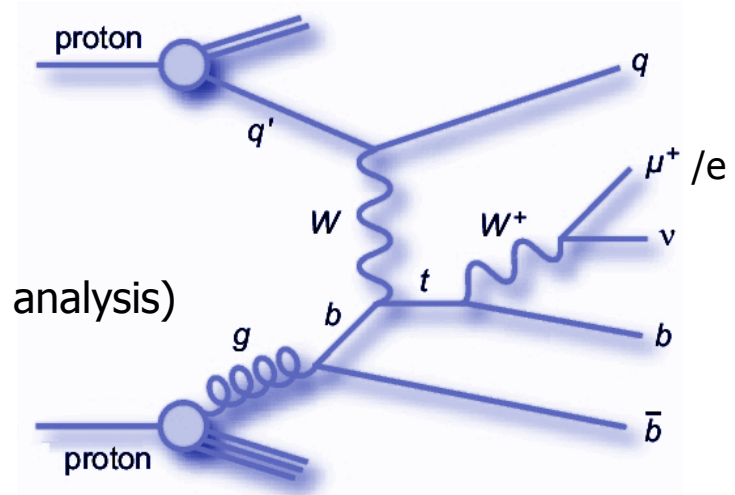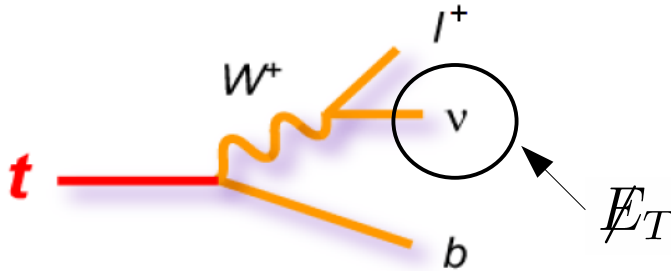
- Solve neutrino z-momentum

- W boson mass constraint
  - real solutions: smaller |p_z|
  - complex solution: minimally modify MEx and MEy

CMS Preliminary, 36 pb^{-1}, $\sqrt{s}$ = 7 TeV

muon channel

W+jets

$t\bar{t}$

signal

data, t channel, s channel, tW, $t\bar{t}$, $Wb\bar{b}$, $Wc\bar{c}$, Wc, W+light jets, Z+jets, VV, QCD

$M_{l\nu\, b}$ (GeV)

CMS Preliminary, 36 pb^{-1}, $\sqrt{s}$ = 7 TeV

electron channel

data, t channel, s channel, tW, $t\bar{t}$, $Wb\bar{b}$, $Wc\bar{c}$, Wc, W+light jets, Z+jets, VV, QCD

$M_{l\nu\, b}$ (GeV)

Still rather small signal to background ratio: Complementary methods

→ Exploit two characteristic features of Single top quark production (**2D analysis**)

→ Use MVA technique Boosted Decision Trees for further separation (**BDT analysis**)

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# Strategy: Two Complementary Methods

- **2D analysis**

  - 2D fit to angular properties of the signal

  - Main backgrounds have very similar shapes

    → Result is robust against background composition
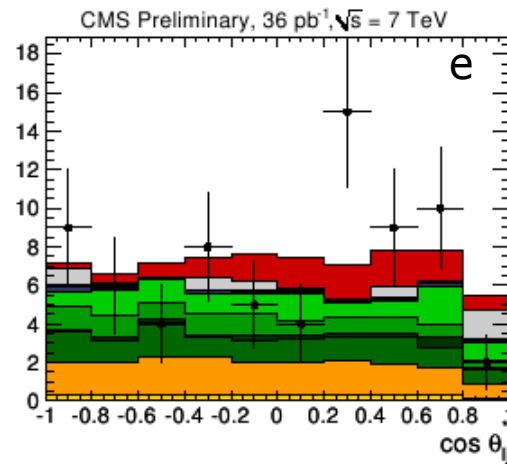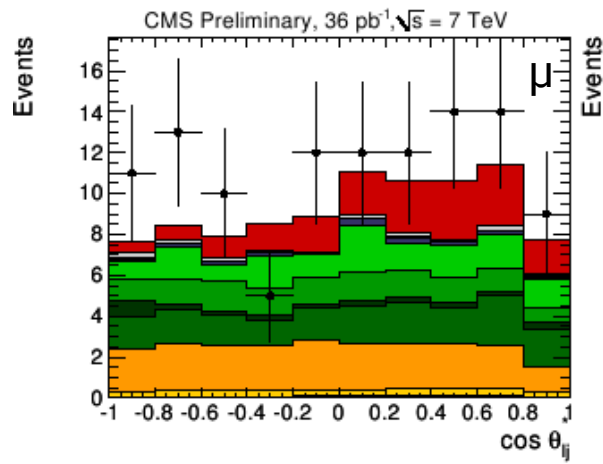
  - **Minimum model dependence**
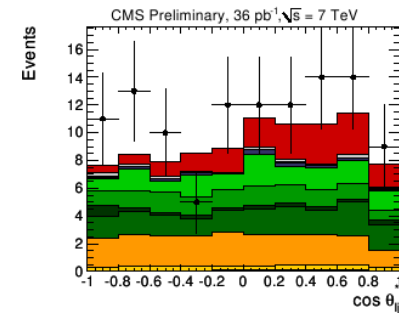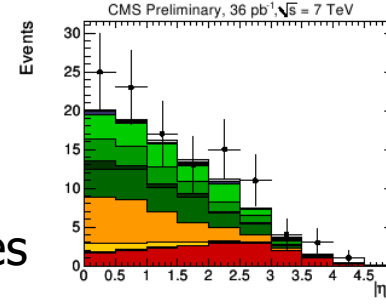
- **BDT analysis**

  - Multivariate analysis

  - Exploits prior knowledge of EW top quark production

    → Probes events on SM Single top quark event topology
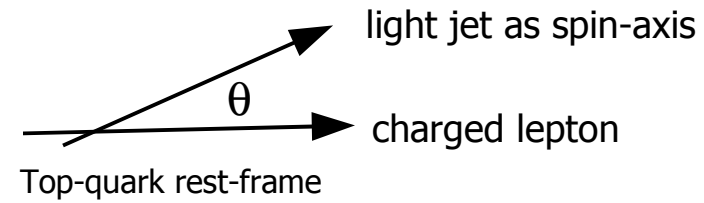
  - **Maximum sensitivity**
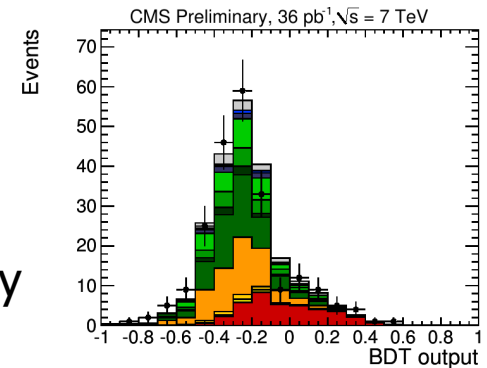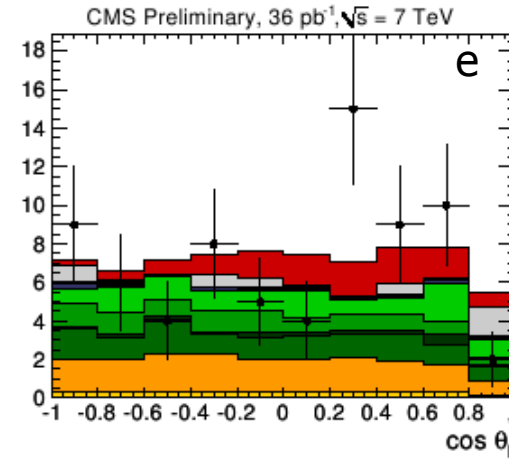
- **Combination** of both results

2D Analysis

CMS Preliminary, 36 pb⁻¹, √s = 7 TeV (μ)

CMS Preliminary, 36 pb⁻¹, √s = 7 TeV (e)

almost 100% left-handed polarization of top-quark

light jet as spin-axis
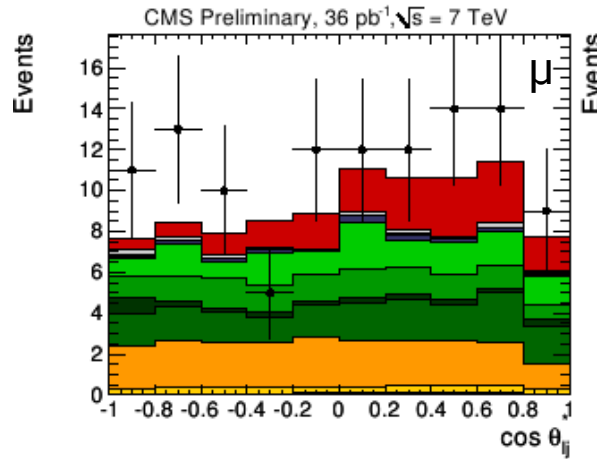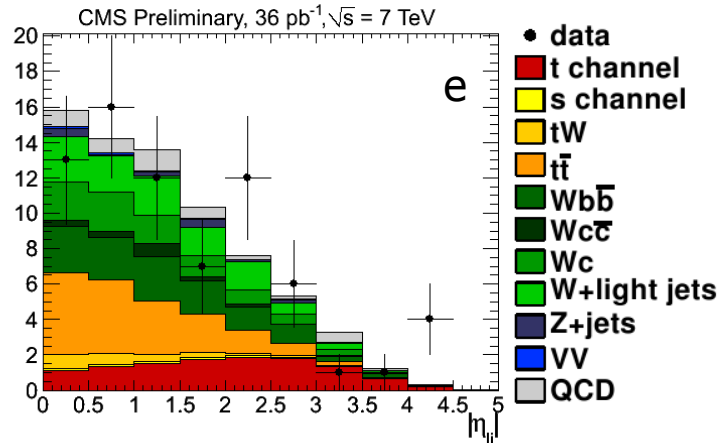
θ

charged lepton

Top-quark rest-frame

2D Analysis
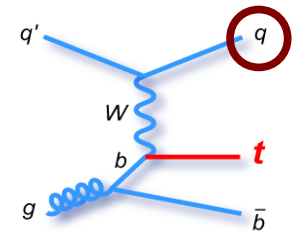

almost 100% left-handed polarization of top-quark

light jet as spin-axis

θ

charged lepton
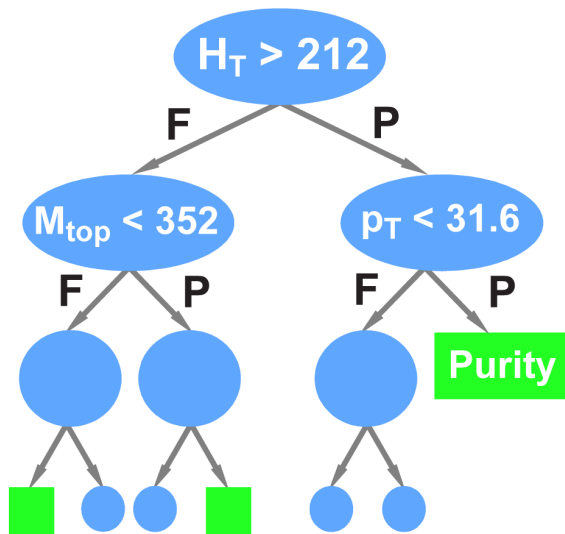
Top-quark rest-frame
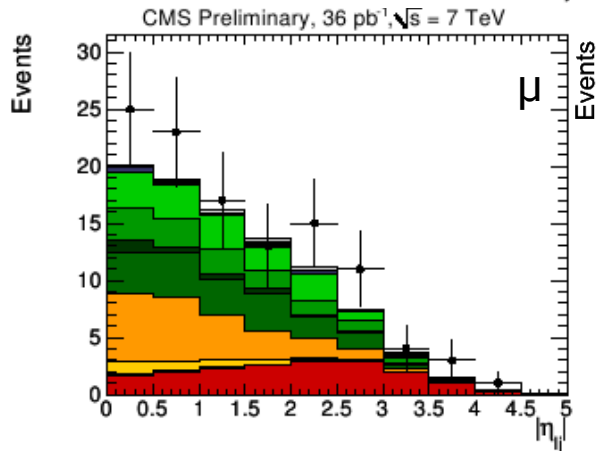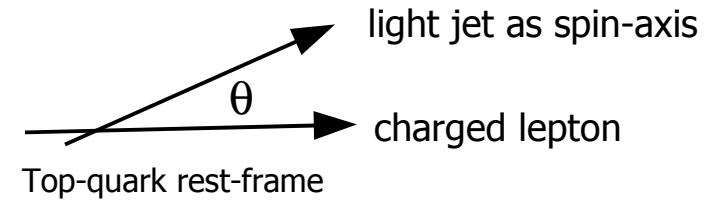
$|\eta|$ (light recoil jet)

- W+light jets shape from data control region for both variables
- Cross section measurement: Perform binned likelihood fit on both variables simultaneously
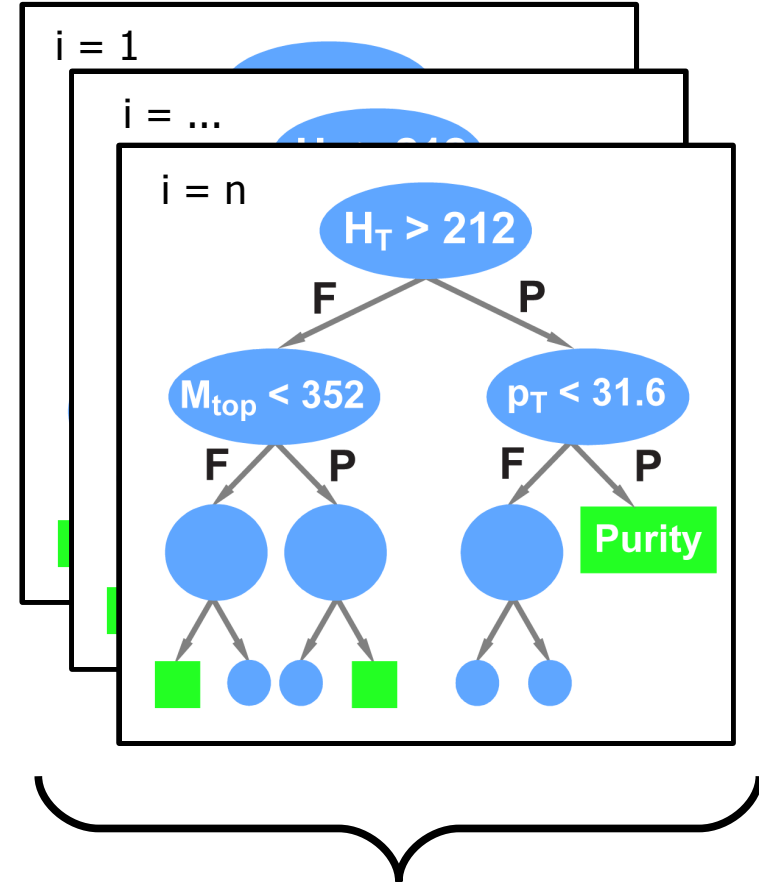- Significance: Dice pseudo-experiments
  → Expected significance: 2.1σ (36pb^{-1})

Separation of Signal and Background Events using Boosted Decision Trees (BDT)
- The Method: BDTs in a nutshell -

Reweight misclassified events

n boosting Cycles

i = 1
i = ...
i = n

leafs denoted as "signal" or "background" like
• Signal events: +1
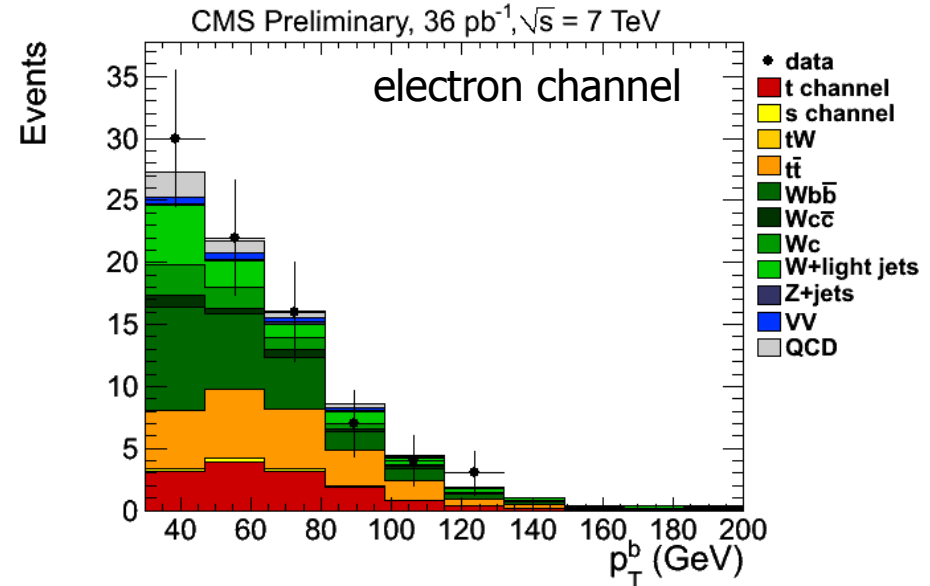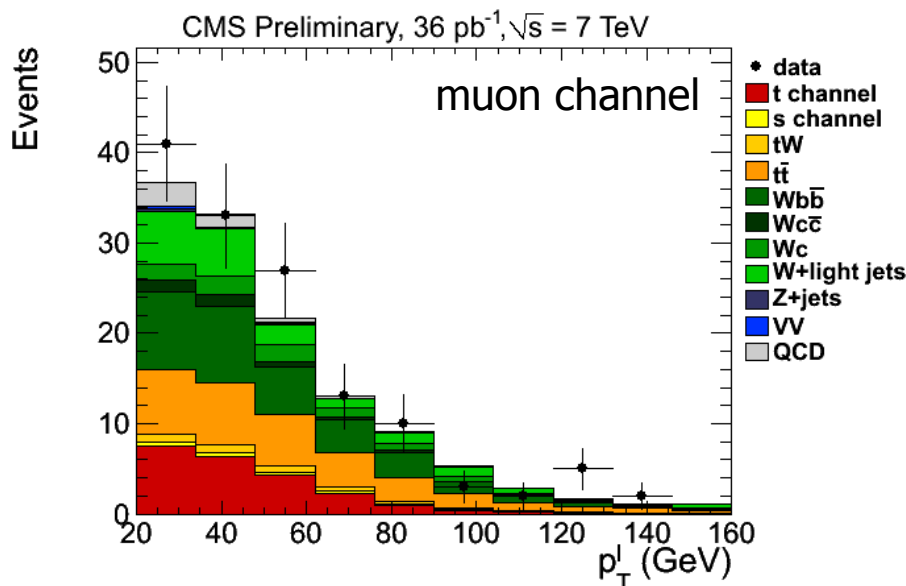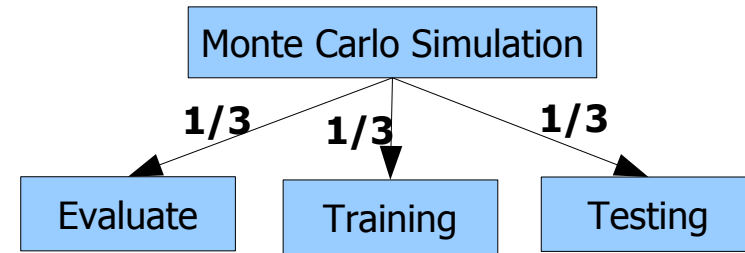• Background events: -1

weighted majority vote

one powerful discriminator:
BDT classifier output

$$y_{Boost}(\vec{x}) = 1/N_{trees} \cdot \sum_{i}^{N_{trees}} ln(\alpha_i) \cdot h_i(\vec{x})$$

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BDT Analysis

- 37 well-modelled input variables in 5 categories:

  - **Kinematics** of final-state objects

  - **Correlations** of final-state objects

  - Properties of **reconstructed W, t, t+q**

  - **Angular distributions** of l,j wrt W,t,t+q

  - **Global event properties**

- **Performed Kolmogorov-Smirnov-Test on W-enriched control sample for each variable: obtained good description of all input variables**

Monte Carlo Simulation

1/3   1/3   1/3

Evaluate   Training   Testing

CMS Preliminary, 36 pb^{-1}, $\sqrt{s}$ = 7 TeV — muon channel

CMS Preliminary, 36 pb^{-1}, $\sqrt{s}$ = 7 TeV — electron channel

Legend: data, t channel, s channel, tW, $t\bar{t}$, $Wb\bar{b}$, $Wc\bar{c}$, Wc, W+light jets, Z+jets, VV, QCD
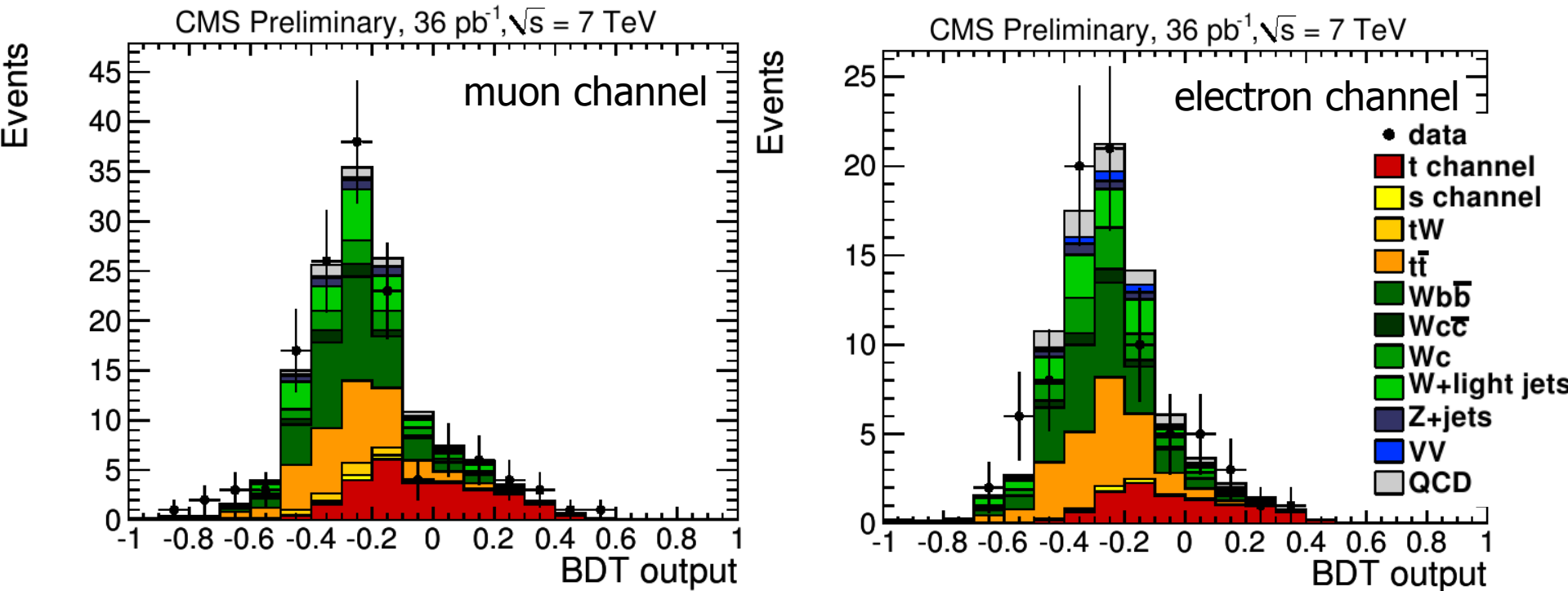
Single top t-channel events separated from background

- Cross section measurement: Bayesian "core method"
  → Treatment of nuisance parameters: Marginalization
- Significance: Dice pseudo-experiments
→ Expected significance: 2.9σ (36pb^{-1})

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Background Estimations

QCD multijet yield (2D and BDT analyses)
- Template fit, 2 components:
  QCD and non-QCD, both unconstrained
- "non-QCD" template from MC
- "QCD" template from an orthogonal sample
  with anti-isolation (reliso>0.2)

  BDT analysis:
  N_{QCD} = 4.92 ± 2.46 (muons)
  N_{QCD} = 5.27 ± 5.27 (electrons)


CMS Preliminary, 36 pb^{-1} at $\sqrt{s}$ = 7 TeV

QCD multijet shape (BDT analysis)
- "QCD" template from an orthogonal sample
  with anti-isolation (reliso>0.2&reliso<0.5)
  without b-tagging requirement

W+light partons yield (2D analysis)
- Template fit in data control regions: 30% (20%) uncertainty in muon (electron) channel
  - without b-tagging requirement
  - with b-tagging requirement loose <= b-tag < tight

- **W+light jets shape (2D analysis)**
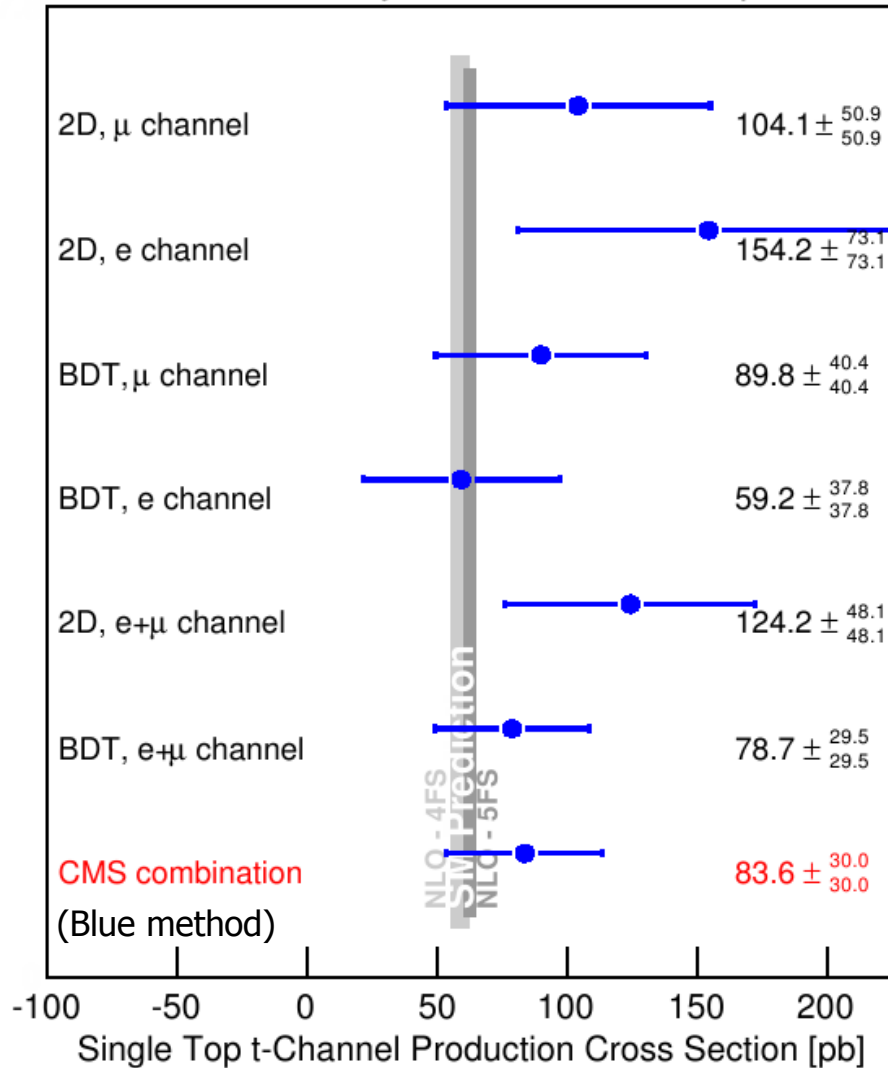 - from data control region without b-tagging requirement
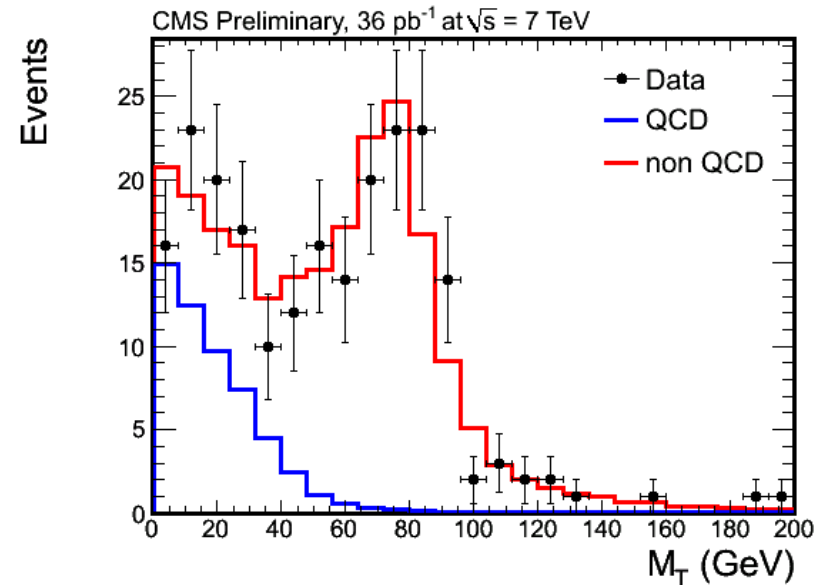
Systematic Uncertainties

uncertainty	correlation	impact on 2D		impact on BDT	
		−	+	−	+
statistical only	60	52		39	
shared shape/rate uncertainties:					
ISR/FSR for $t\bar{t}$	100	−1.0	+1.5	< 0.2	< 0.2
Q^2 for $t\bar{t}$	100	+3.5	−3.5	+0.3	−0.4
Q^2 for V+jets	100	+5.7	−12.0	+2.6	−4.5
Jet energy scale	100	−8.8	+3.6	−5.1	+1.2
b tagging efficiency	100	−19.6	+19.8	−15.2	+14.6
MET (uncl. energy)	100	−5.7	+3.7	−3.9	−0.5
shared rate-only uncertainties:					
$t\bar{t}$ (±14%)	100	+2.0	−1.9	+0.5	−0.6
single top s (±30%)	100	−0.4	+0.5	−0.4	+0.4
single top tW (±30%)	100	+1.1	−1.0	< 0.2	< 0.2
$Wb\bar{b}$, $Wc\bar{c}$ (±50%)	100	−3.0	+2.9	+1.7	−1.9
Wc $\left(^{+100\%}_{-50\%}\right)$	100	−3.0	+6.1	−2.4	+4.4
Z+jets (±30%)	100	−0.6	+0.7	+0.4	−0.2
electron QCD (BDT: ±100%, 2D: $^{+130\%}_{-100\%}$)	50	+2.9	−3.7	−1.7	+1.7
muon QCD (BDT: ±50%, 2D: ±50%)	50	< 0.2	< 0.2	−2.1	+2.1
signal model	100	−5.0	+5.0	−4.0	+4.0
BDT-only uncertainties:					
electron efficiency (±5%)	0	—	—	−1.4	+1.4
muon efficiency (±5%)	0	—	—	−3.6	+3.5
V+jets (±50%)	0	—	—	−1.5	< 0.2
2D-only uncertainties:					
muon W+light (±30%)	0	−1.4	+1.4	—	—
electron W+light (±20%)	0	−0.6	+0.7	—	—
W+light model uncertainties	0	−5.4	+5.4	—	—

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Combination and Results

CMS Preliminary, $\sqrt{s}=7$ TeV, L=35.9 pb[1]

Channel	Cross Section [pb]
2D, μ channel	$104.1 \pm {}^{50.9}_{50.9}$
2D, e channel	$154.2 \pm {}^{73.1}_{73.1}$
BDT, μ channel	$89.8 \pm {}^{40.4}_{40.4}$
BDT, e channel	$59.2 \pm {}^{37.8}_{37.8}$
2D, e+μ channel	$124.2 \pm {}^{48.1}_{48.1}$
BDT, e+μ channel	$78.7 \pm {}^{29.5}_{29.5}$
CMS combination (Blue method)	$83.6 \pm {}^{30.0}_{30.0}$

Single Top t-Channel Production Cross Section [pb]

Expected significance	Observed significance
1.7	2.5
1.3	3.1
2.4	3.1
2.0	1.9
2.1	**3.7**
2.9	**3.5**

Combination and Results

CMS Preliminary, $\sqrt{s}$=7 TeV, L=35.9 pb[1]

	Expected significance	Observed significance
2D, μ channel	1.7	2.5
2D, e channel	1.3	3.1
BDT, μ channel	2.4	3.1
BDT, e channel	2.0	1.9
2D, e+μ channel	**2.1**	**3.7**
BDT, e+μ channel	**2.9**	**3.5**

$$|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}} = 1.16 \pm 0.22(exp) \pm 0.02(th)$$

For $0 \leq |V_{tb}|^2 \leq 1$ (flat prior in $|V_{tb}|^2$):

$|V_{tb}| > 0.69$ @95% CL (BDT analysis)

Assumption: $|V_{td}|, |V_{ts}| \ll |V_{tb}|$ => BR(t→b)~1

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Conclusion

CMS Preliminary, 36 pb^{-1}, $\sqrt{s}$ = 7 TeV

electron + muon

t-channel single top quark production
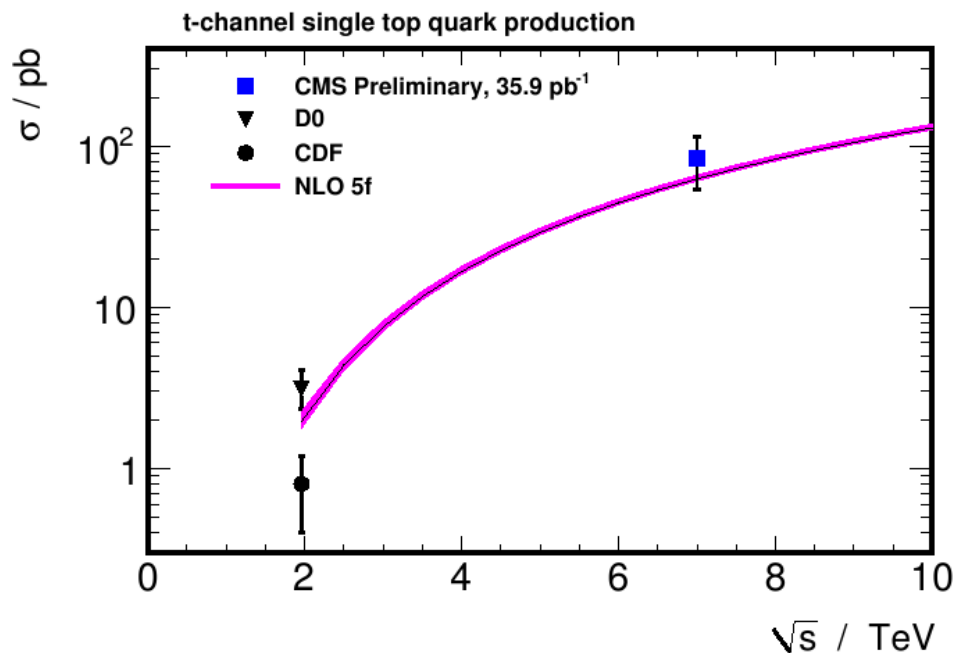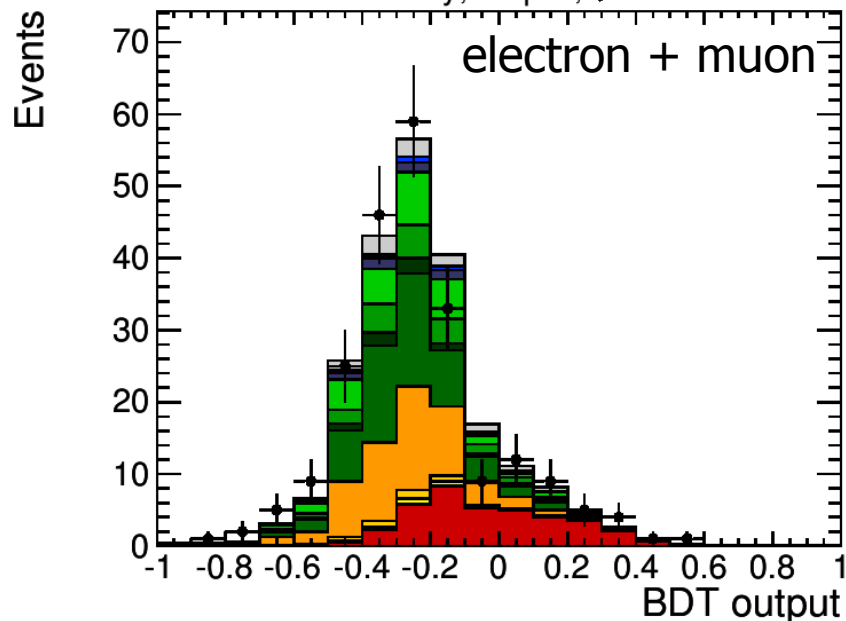
$$\sigma = 83.6 \pm 29.8(stat. + syst.) \pm 3.3(lumi.) \text{ pb}$$

Observed significance: 3.5σ (BDT) and 3.7σ (2D)

- **First measurement of single top quark t-channel production at 7 TeV**
  - **First measurement of single top quark t-channel without MVA**
    - **Consistent with Standard Model**
    - **36% precision with 2010 data**

Backup

BDT Analysis

Comparison of BDT output in Monte Carlo simulation:

t-Channel: SINGLETOP, MADGRAPH, MC@NLO

Top quark pair: MADGRAPH, MC@NLO, Pythia

→ Negligible shape differences

BDT output in data:
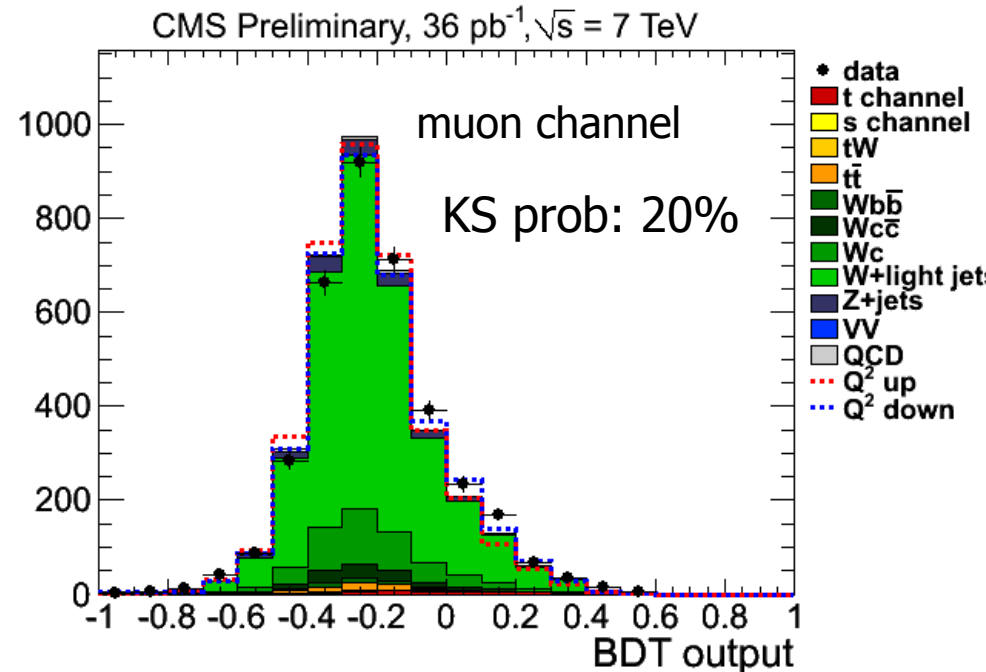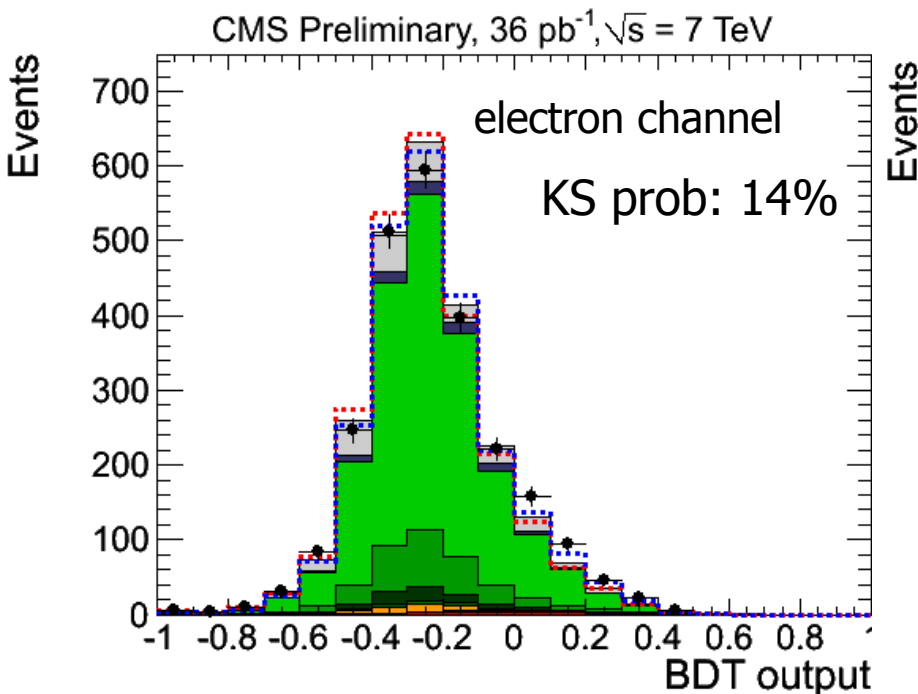
Shape comparison of BDT output in W+Jets enriched control region
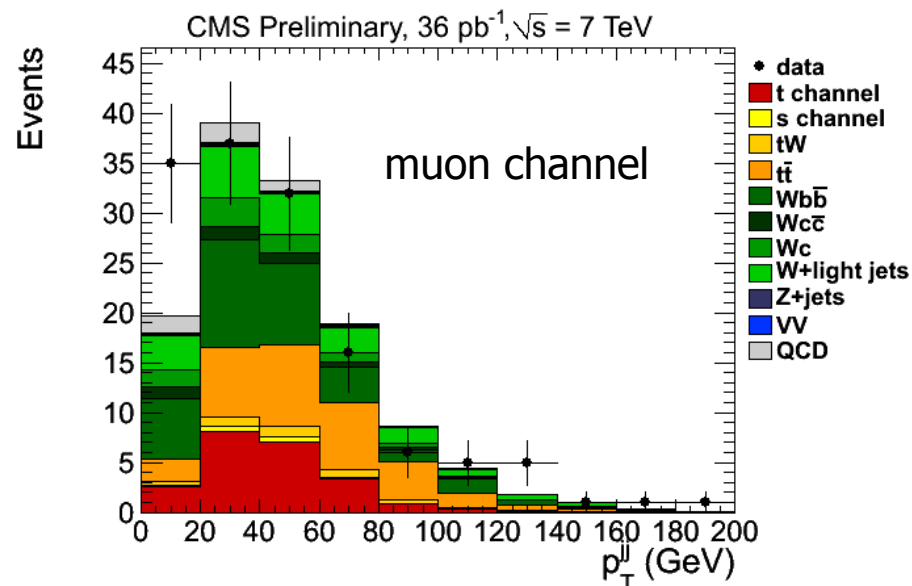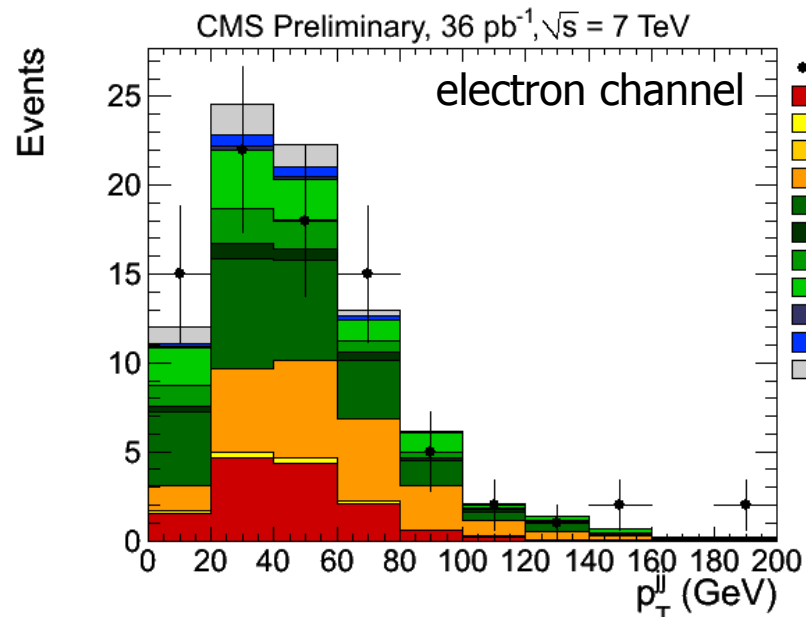
"MC out of the box"

BDT Analysis
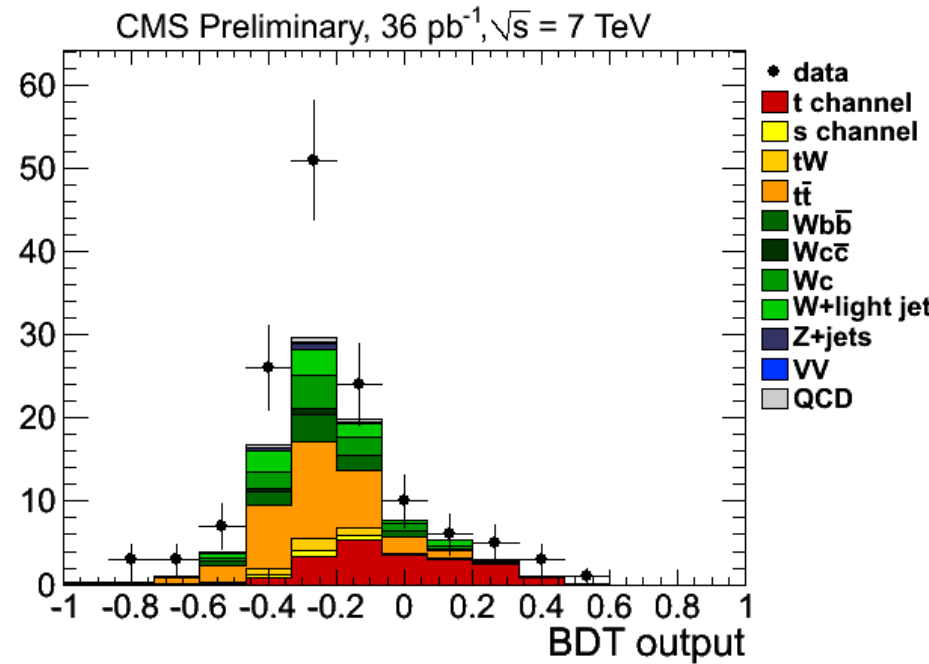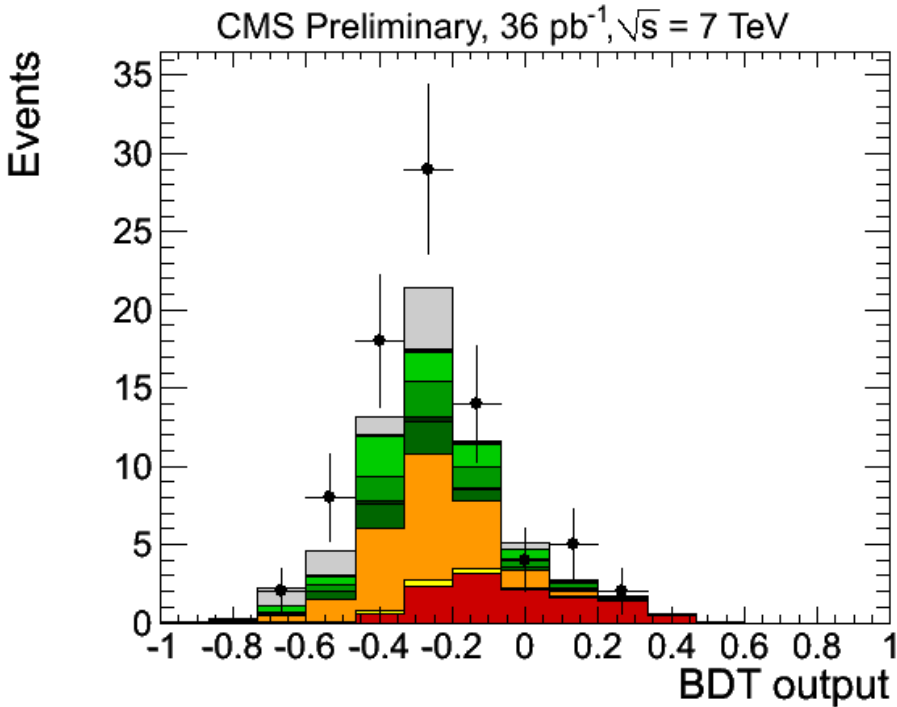
BDT output in after full selection

"MC out of the box" and
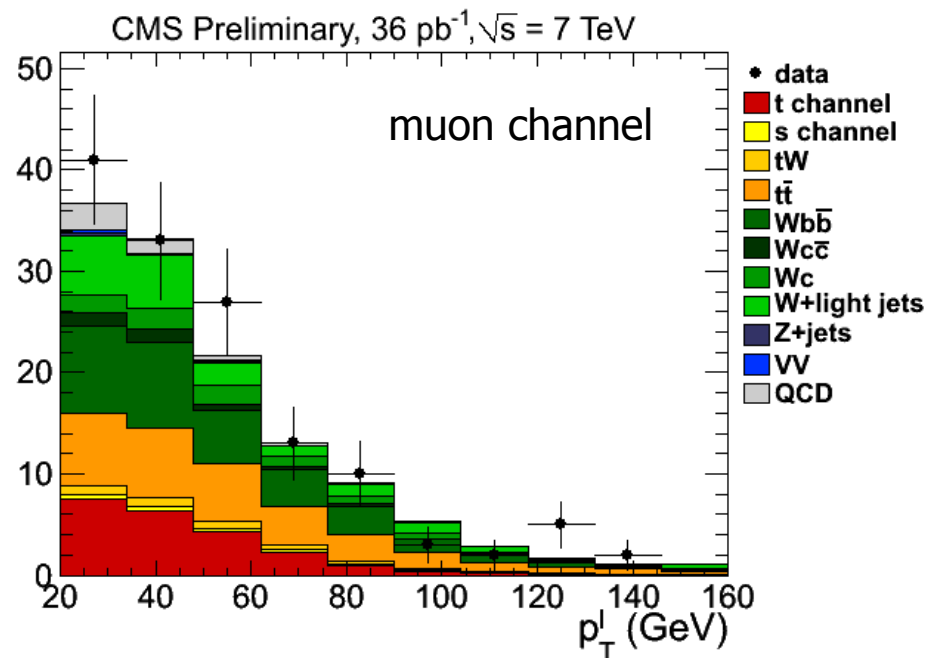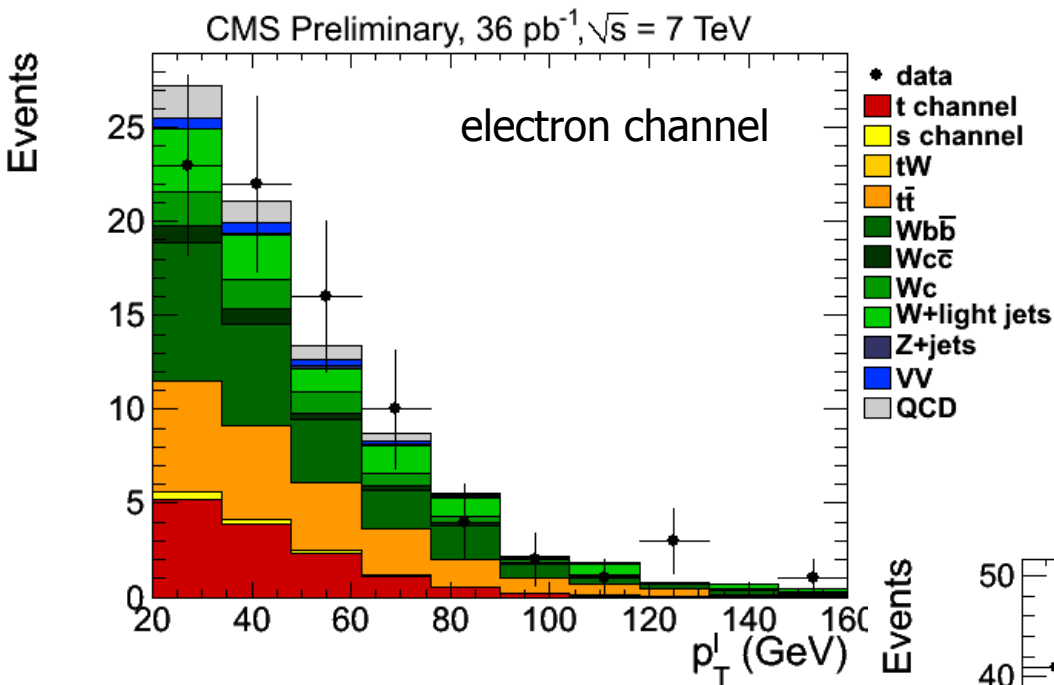(individual processes not scaled to most probable values after statistical evaluation)

The top 5 discriminating variables
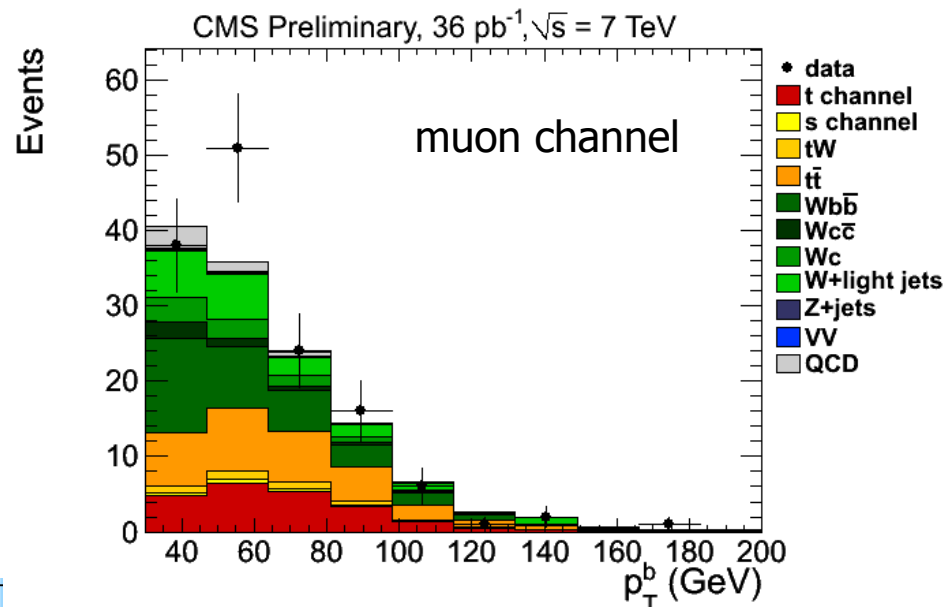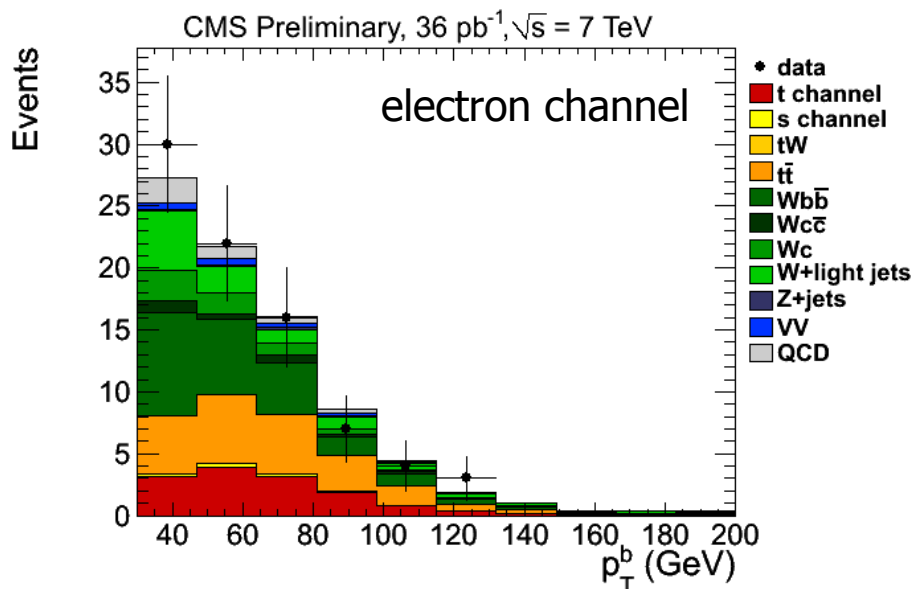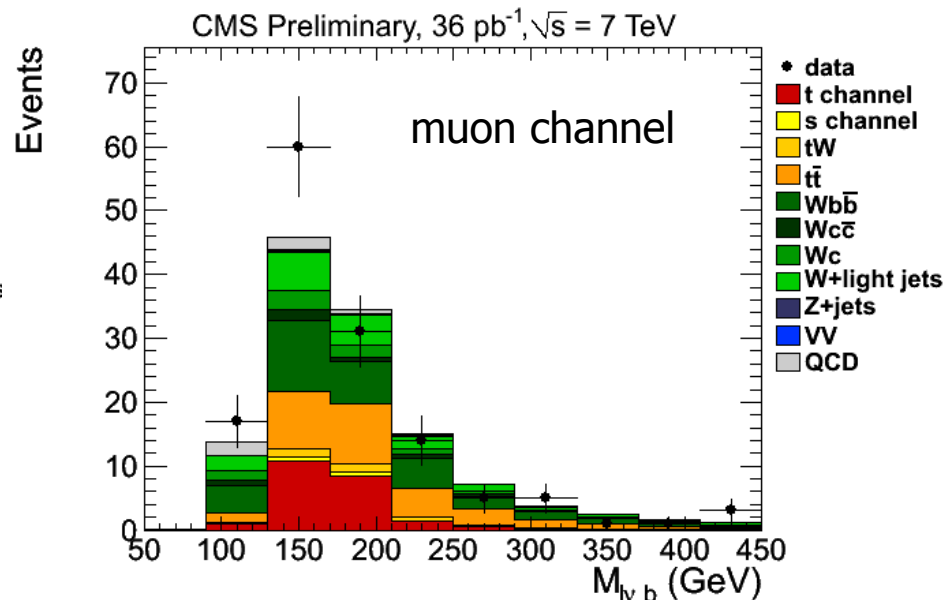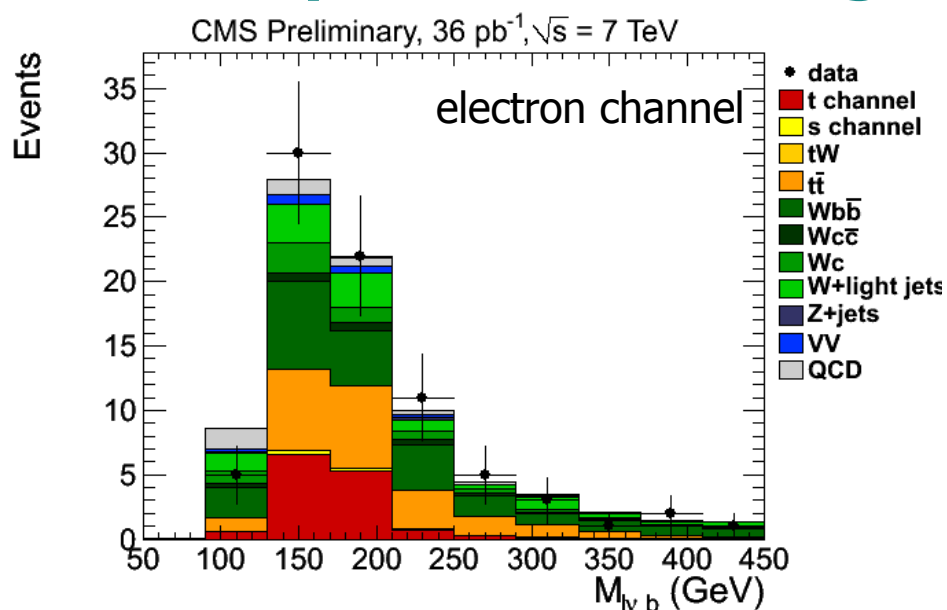
The top 5 discriminating variables
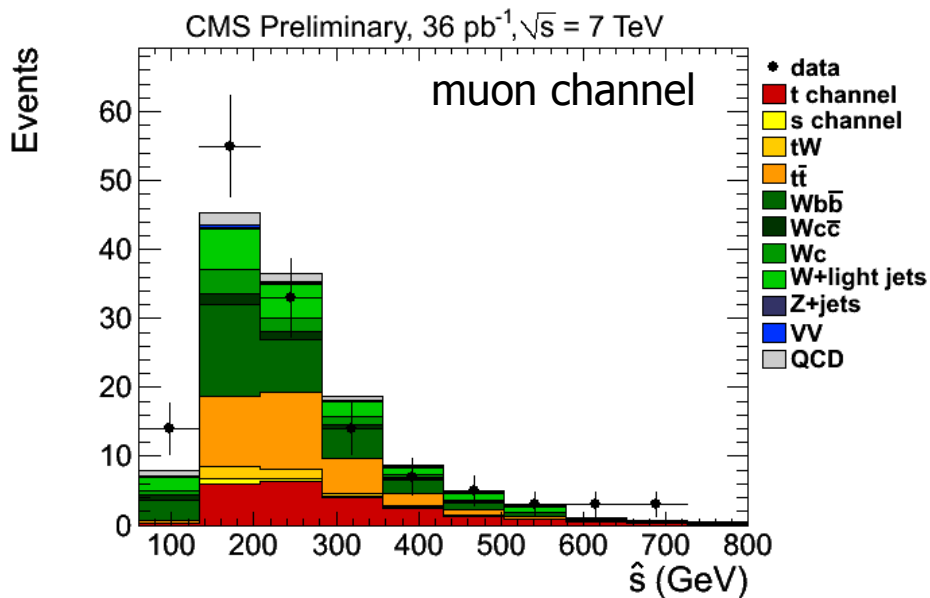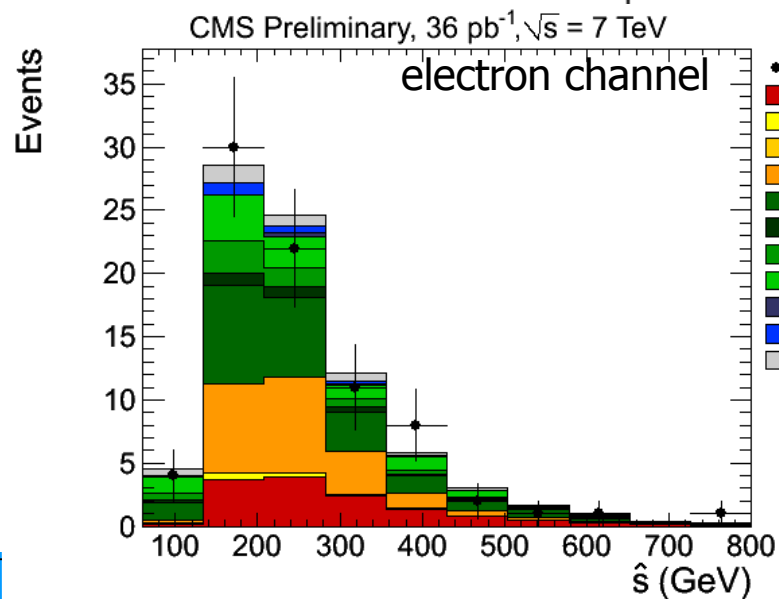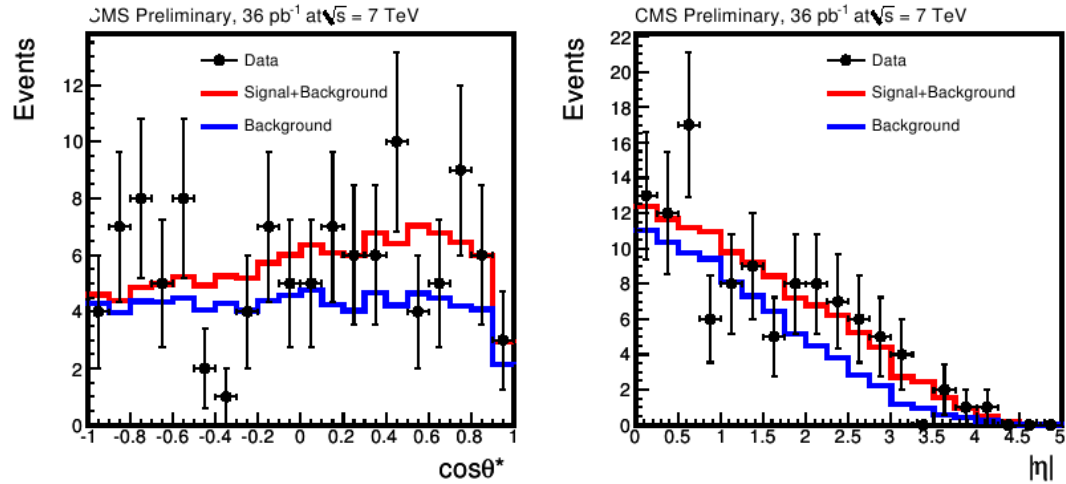
The top 5 discriminating variables

2D fit

Figure 11: Projections of the 2D fit to $\cos\theta^*_{lj}$ (left) and η_{lj} (right) in the muon decay channel.
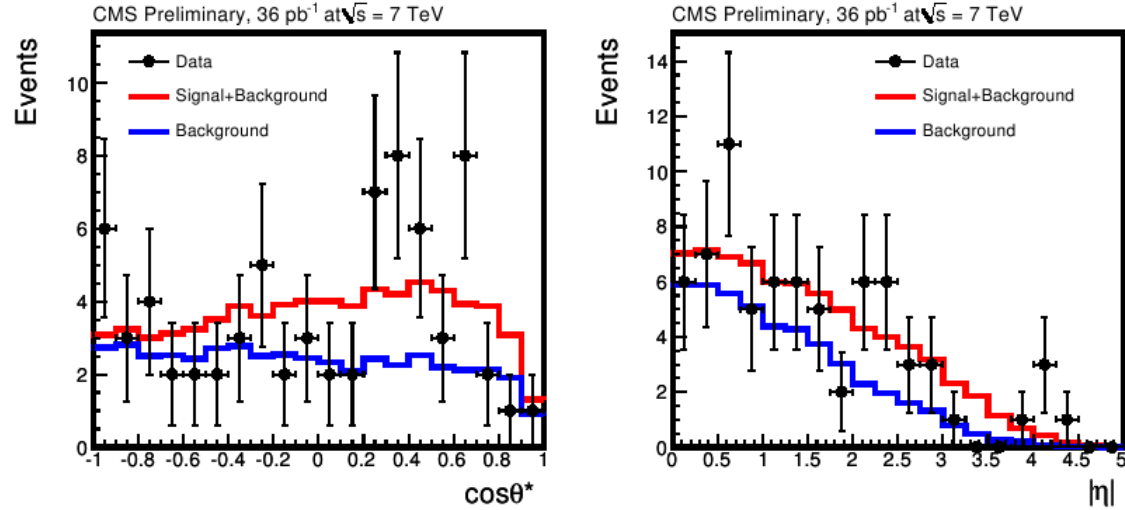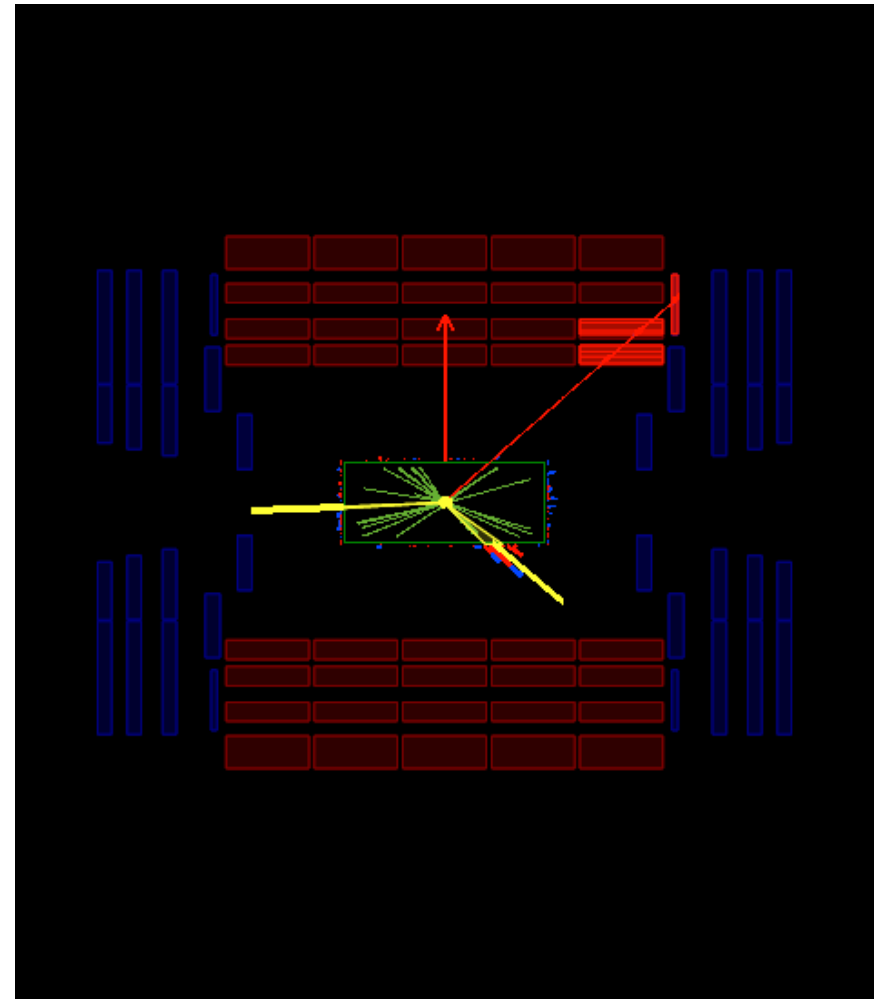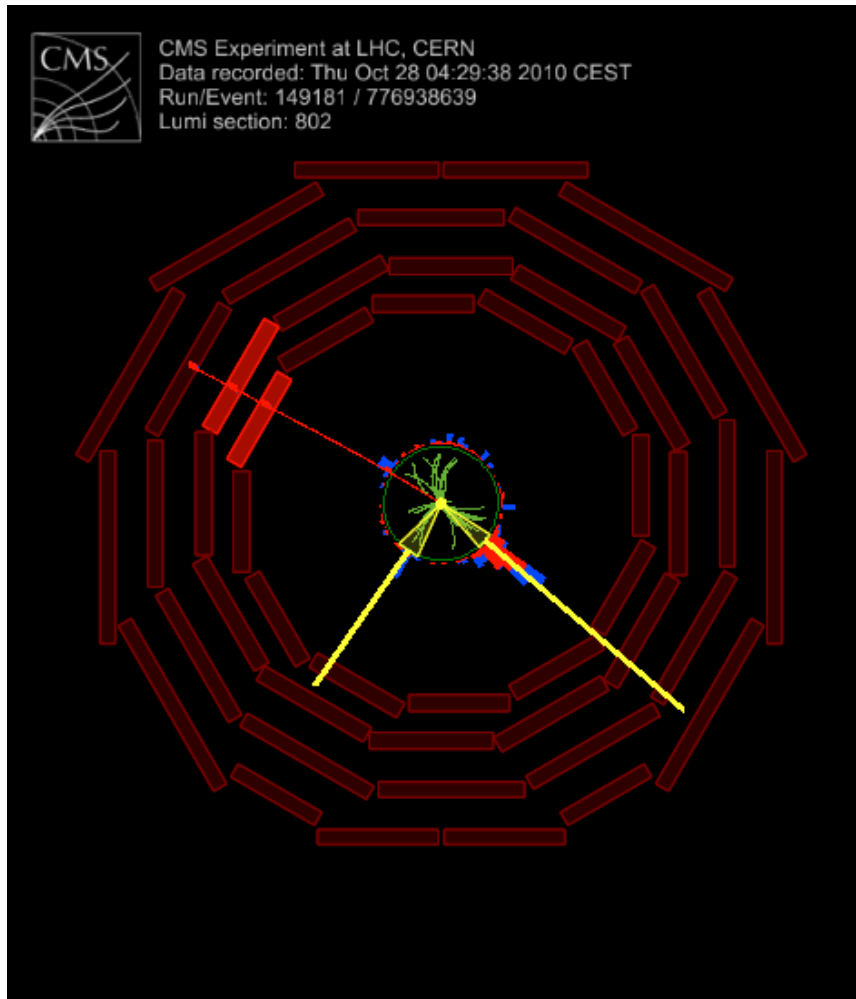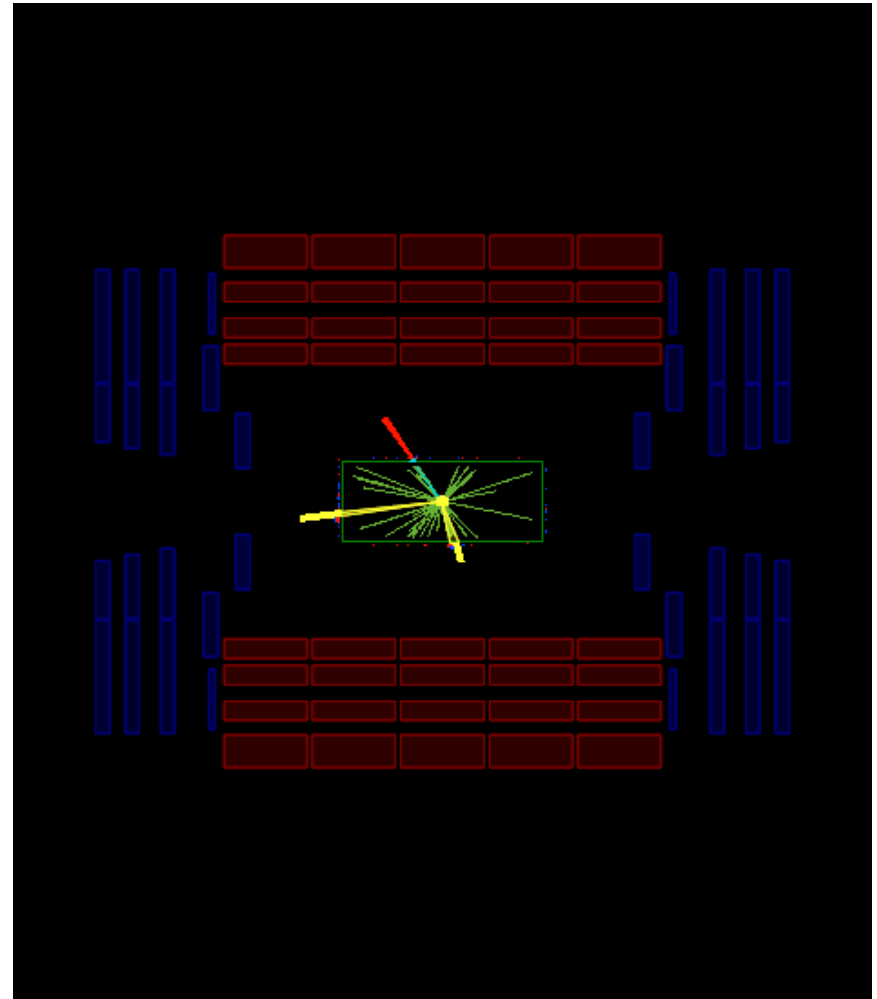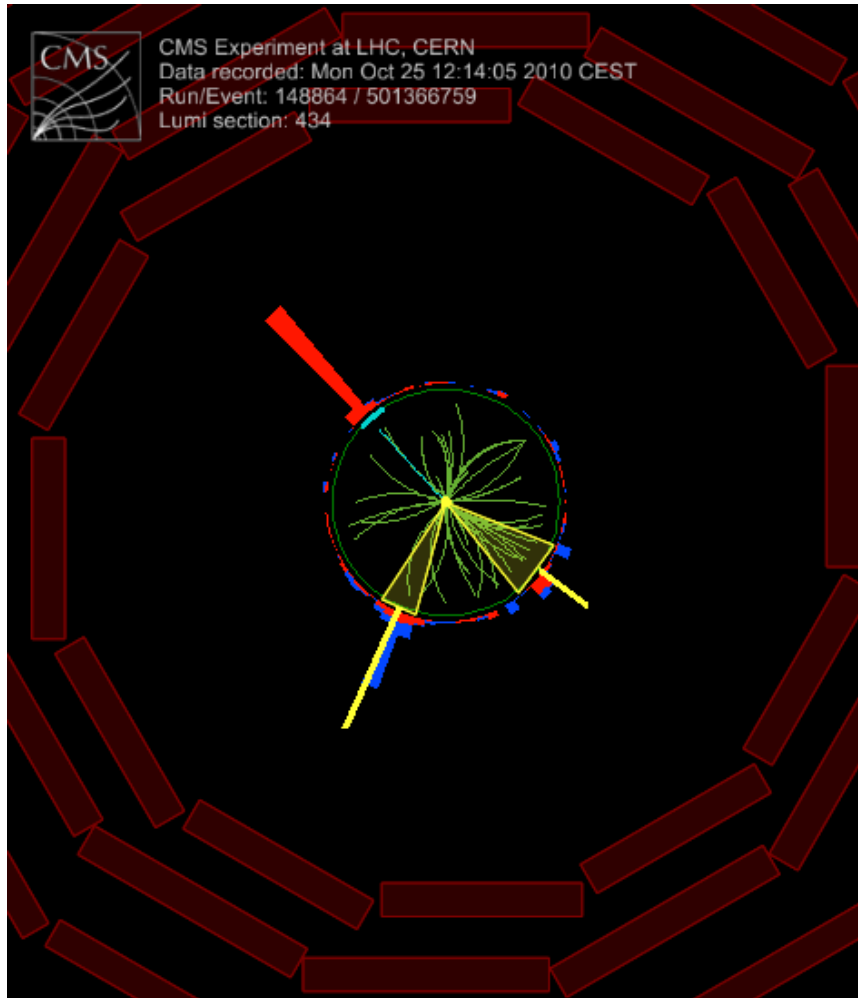

Figure 12: Projections of the 2D fit to $\cos\theta^*_{lj}$ (left) and η_{lj} (right) in the electron decay channel.

Most signal-like according to the BDT; it also passes the 2D selection
$\cos\theta_{lj}^* = 0.24$, $\eta_{lj} = -3.76$

Golden electron candidate

Most signal-like according to the BDT; it also passes the 2D selection
$\cos\theta_{lj}^{*}=0.23$, $\eta_{lj}=-2.84$